Gold Standard for the Global Goals

METHODOLOGY – SUPPLEMENTARY INFORMATION

GS4GG PAA MT400-09 SI

SDG 13

ANALYSIS OF LOCK-IN RISK

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TABLE OF CONTENTS

1| DEFAULT TECHNICAL AND OPERATIONAL LIFETIME FOR COMMON MITIGATION TECHNOLOGIES (ANNEX A):

EXECUTIVE SUMMARY

Under the Gold Standard for the Global Goals (GS4GG) Methodology Tool: Analysis of Lock-in Risk (GS4GG PAA MT400-XX), mitigation activity developers shall accurately determine the operational or technical lifetime of proposed mitigation technologies (Step 1). This parameter serves as a critical regulatory threshold: technologies with a lifespan exceeding 10 years are subject to rigorous greenhouse gas (GHG) intensity and resource efficiency assessments (Steps 3 and 4) to prevent macroeconomic carbon lock-in, whereas shorter-lived technologies (≤10 years) qualify for a temporary sunset exemption valid until December 31, 2030. This supplementary research report synthesizes authoritative engineering and techno-economic literature. Based on data from the Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA), National Renewable Energy Laboratory (NREL), and the United Nations Framework Convention on Climate Change (UNFCCC), this assessment establishes scientifically backed default lifespans across multiple sectors. It culminates in a formal recommendation for a Default Lifetime Reference Table to be adopted as a normative annex to the GS4GG Lock -In risk Analysis Tool.

1.1 | Introduction and Procedural Context

Carbon lock-in refers to the systemic inertia created by large, capital-intensive investments in infrastructure that perpetuates emissions-intensive trajectories and actively hinders a host country's transition to a net-zero economy (Seto et al., 2016). Within the GS4GG Tool, assessing the operational lifetime of a technology is the critical first step in quantifying and mitigating this risk.

The GS4GG Analysis of Lock-in Risk Tool establishes a bifurcated assessment pathway based on equipment lifespan. Delegating the determination of technology lifetimes entirely to project developers introduces a significant proof of burden: developers may subjectively under-report equipment lifespans to bypass the stringent contextualized alternative-scenario modelling required in Step 3. Therefore, to ensure standard application, reduce validation friction for Verification and Validation Bodies (VVBs), and maintain environmental integrity, GS4GG presents a normative default lifetime table (stipulated as "Option 1: Default Values (Preferred)" in the tool). This report provides the evidentiary basis for that table.

1.2 | Methodology of the Literature Review

To establish the recommended default lifetimes, a systematic literature review was conducted. The criteria for selecting authoritative values were strictly defined to eliminate outlier data and ensure global applicability:

a. Hierarchy of Sources: Institutional life-cycle assessments and bottom-up engineering models (IEA, NREL, IPCC) were prioritized, followed by formal regulatory carbon market defaults (UNFCCC CDM and Article 6.4 tools), and lastly, peer-reviewed longitudinal field studies.

b. The Conservativeness Principle: Where literature presented a lifespan range (e.g., 20–30 years for solar PV), the upper bound (longest lifespan) was systematically selected. In the context of lock-in risk, assuming a longer lifespan is the conservative approach, as it forces the activity into the rigorous Step 3 and 4 assessments rather than allowing an unjustified exemption.
c. Operational vs. Financial: Lifetimes were strictly evaluated based on technical and operational durability (the physical period the equipment dictates an emissions profile), explicitly disregarding shorter financial depreciation or cost-recovery schedules.

1.3 | Review of Authoritative Lifetimes by Technology Sector

1.3.1 | Macro-Scale Renewable Energy & Grid Infrastructure

Renewable energy assets are fundamentally long-lived capital investments. According to the NREL Annual Technology Baseline (ATB), modern utility-scale Solar Photovoltaic (PV) systems exhibit an operational lifetime of 30 years, driven by reductions in the degradation rates of crystalline silicon modules to roughly 0.5% per year (NREL, 2023a). Commercial and residential PV systems, limited by roof lifespans and smaller inverters, are benchmarked at 25 years (NREL, 2024). Similarly, onshore and offshore wind turbines are engineered for a 25- to 30-year lifespan before fatigue loads on the drivetrain necessitate repowering (IEA, 2020; NREL, 2023b). Hydropower infrastructure demonstrates the longest operational permanence; while electro-mechanical equipment (turbines, generators) requires refurbishment every 40 years, the civil works (dams) operate for over 80 years (UNFCCC, 2023).

1.3.2 | Household and Decentralized Technologies

Mitigation activities at the household level exhibit highly variable lifespans based on material durability and user handling. A definitive longitudinal field study in Ethiopia tracking the retention of biomass improved cookstoves (ICS) determined a functional lifespan of 3 to 5 years before structural failure mandated abandonment (Beyene et al., 2015). Advanced institutional rocket stoves or high-tier metal gasifiers are generally allocated a maximum lifespan of 7 years based on independent field testing (Clean Cooking Alliance, 2022). Conversely, household brick-and-mortar biogas digesters, which involve fixed civil construction, reliably operate for 15 to 20 years with minor maintenance (Wang et al., 2014; UNFCCC, 2023).

1.3.3 | Industrial Systems and Thermal Heating

Industrial capital stock is recognized by the IPCC as possessing the highest lock-in risk due to slow stock turnover rates and high capital costs (IPCC, 2022). For industrial heating and power, the UNFCCC *Methodological tool: Determination of the technical lifetime of equipment* provides well-established default values: industrial boilers and steam turbines are standardized at 25 years, while industrial chillers, HVAC networks, and heavy electric motors operate for approximately 15 years (UNFCCC, 2023). Standby or continuous-use fossil fuel generators are rated for 50,000 operational hours, translating to a 15- to 20-year span in typical base-load profiles.

1.3.4 | Engineered Carbon Removals (DACCS, BECCS)

Emerging engineered removals require massive resource inputs and are modelled with lifespans comparable to heavy industrial chemical plants. Life Cycle Assessments (LCAs) standardized by the U.S. Department of Energy (DOE) and independent techno-economic models assume a nominal operational plant lifetime of 25 years for Direct Air Capture with Carbon Storage (DACCS) facilities before major facility reconstruction is necessary (U.S. DOE, 2022; Realmonte et al., 2019). Bioenergy with CCS (BECCS) facilities are similarly modelled with a 25- to 30-year operational lifetime (IPCC, 2022).

1.4 | Recommended Default Lifetime Reference Table

Based on the synthesized literature, it is recommended that the following reference table be formally adopted as an Annex to the GS4GG PAA MT400-XX Methodology Tool.

Table 1: GS4GG Default Technical and Operational Lifetimes for Mitigation Technologies

Sector / Technology Category	Specific Technology / Practice	Default Lifetime (Years)	Lock-in Pathway (10-Year Exemption Eligibility)	Primary Authoritative Source
Renewable Energy	Solar PV (Utility-Scale)	**30**	Deep-Dive (>10 Yrs)	NREL (2023a)
	Solar PV (Commercial/Residential)	**25**	Deep-Dive (>10 Yrs)	NREL (2024)
	Wind (Onshore and Offshore)	**25**	Deep-Dive (>10 Yrs)	IEA (2020); NREL (2023b)
	Hydropower (Electro-mechanical)	**40**	Deep-Dive (>10 Yrs)	UNFCCC (2023)
Household & Distributed	Basic Improved Cookstoves (Clay/Metal)	**4**	Fast-Track (≤10 Yrs)	Beyene et al. (2015)
	Advanced Biomass/Pellet Cookstoves	**7**	Fast-Track (≤10 Yrs)	Clean Cooking Alliance (2022)

	LED Lighting & Solar Lanterns	**5 to 10**	Fast-Track (≤10 Yrs)	IEA (2020)
	Fixed-Dome/Masonry Biodigesters	**20**	Deep-Dive (>10 Yrs)	Wang et al. (2014); UNFCCC (2023)
Industrial & Thermal	Industrial Boilers (Biomass or Fossil)	**25**	Deep-Dive (>10 Yrs)	UNFCCC (2023)
	Commercial HVAC / Chillers	**15**	Deep-Dive (>10 Yrs)	UNFCCC (2023)
	Fossil Fuel Generators (Diesel/Gas)	**20**	Deep-Dive (>10 Yrs)	UNFCCC (2023)
Engineered Removals	Direct Air Capture (DACCS) Facilities	**25**	Deep-Dive (>10 Yrs)	U.S. DOE (2022); Realmonte et al. (2019)
	Bioenergy with CCS (BECCS) Plants	**25**	Deep-Dive (>10 Yrs)	IPCC (2022)
AFOLU (Practice Duration)	Regenerative Ag / Soil Interventions	**Contract Based (1–5)**	Fast-Track (≤10 Yrs)	Assessed per land contract
	Commercial Timber / Afforestation	**Contract Based (20+)**	Deep-Dive (>10 Yrs)	Assessed per land contract

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2| "LOCK-IN SAFE" POSITIVE LIST (ANNEX B)

SUMMARY

Under the newly drafted Gold Standard for the Global Goals (GS4GG) Methodology Tool: Analysis of Lock-in Risk (GS4GG PAA MT400-XX), mitigation activities undergo a bifurcated assessment pathway based on their inherent lock-in risk profile. Track A (Fast-Track Assessment) allows inherently low-risk projects to completely bypass complex, macroeconomic greenhouse gas (GHG) modelling (Step 3) and resource efficiency thresholds (Step 4). The tool requires a normative, pre-approved "Lock-in Safe" Positive List. This supplementary research report provides the scientific and socio-economic justification for standardizing this list. By synthesizing frameworks and literature from the World Health Organization (WHO), the Food and Agriculture Organization (FAO), the World Bank, and the Clean Cooking Alliance, this report defines a taxonomy of decentralized, high-impact sustainable development activities that inherently lack the physical, structural, or scale capacity to cause macroeconomic carbon or resource lock-in. It culminates in a formally recommended Positive List Matrix to be adopted as Annex B of the tool.

2.1 | Introduction and Procedural Context

The concept of "carbon lock-in" fundamentally describes a macroeconomic phenomenon driven by massive, capital-intensive investments in centralized infrastructure (e.g., fossil-fuel power plants, vast industrial networks, and large-scale sovereign land acquisitions). These investments create structural "path dependencies" that bind a host country to an emissions-intensive trajectory for decades, actively hindering the transition to superior alternatives (Seto et al., 2016).

Conversely, voluntary carbon markets actively support millions of decentralized, micro-scale interventions aimed at alleviating poverty and meeting basic human needs (e.g., distributing point-of-use water filters, household clean cookstoves, and smallholder agroforestry support). Forcing the developer of a rural water filter project to conduct a macroeconomic assessment of national grid capacities and alternative technological counterfactuals is both scientifically nonsensical and financially prohibitive. Subjecting these project developers to the exhaustive modelling required in Steps 3 and 4 of the tool provides zero additional environmental integrity while disproportionately penalizing projects that deliver the highest direct SDG impacts to vulnerable populations.

To protect equitable access to carbon finance, GS4GG requires a standardized **"Lock-in Safe" Positive List (Annex B)**. Activities employing technologies on this list are deemed universally safe by default, allowing developers to automatically qualify for Track A and bypass Steps 3 and 4, provided they pass basic policy alignment checks (Step 2).

2. Methodology of the Literature Review

To ensure environmental integrity is maintained and the list resists exploitation by large-scale developers, the criteria for inclusion on the Positive List were strictly defined. A technology or practice was only considered "Lock-in Safe" if it met all three of the following conditions:

1. **Inherent Decentralization and Micro-Scale:** The technology shall be deployed at the individual household, smallholder farmer, or localized community level. It shall inherently lack the aggregated physical scale to monopolize national grids, macro-watersheds, or sovereign land-use planning.
2. **Absolute Baseline Substitution:** The technology shall represent an absolute transition away from a highly emissive or ecologically destructive baseline (e.g., completely displacing open-fire three-stone cooking or kerosene lighting) rather than a mere marginal efficiency improvement to an existing fossil-fuel system.
3. **No Structural Path Dependency:** The deployment of the technology shall not create infrastructural inertia that would block the future adoption of even cleaner technologies. (For example, buying a household solar lantern does not prevent a household from connecting to a national green grid ten years later).

2.2 | Review of Authoritative "Lock-in Safe" Technologies by Sector

2.2.1 | Household Energy and Clean Cooking

a. **Context:** Over 2.3 billion people globally rely on traditional biomass and polluting fuels for cooking, driving severe deforestation and black carbon emissions.

b. **Literature:** The WHO Guidelines for Indoor Air Quality and the Clean Cooking Alliance mandate a transition to higher-tier cooking solutions. Advanced biomass/pellet cookstoves (ISO Tier 3 and above), household biogas digesters (typically $\leq 15m^3$ volumetric capacity), and solar cookers completely displace traditional baseline emissions without creating infrastructural lock-in (WHO, 2014; Clean Cooking Alliance, 2022). Household biogas, in particular, utilizes exclusively localized organic waste, completely neutralizing any risk of macro-level sustainable biomass depletion (Wang et al., 2014).

2.2.2 | Decentralized WASH (Water, Sanitation, and Hygiene)

a. **Context:** In regions lacking centralized water purification, households boil water using non-renewable biomass or fossil fuels, which is a massive driver of baseline emissions.

b. **Literature:** Point-of-use (POU) water purification systems, such as gravity-fed ceramic filters, and manual, non-motorized boreholes require absolutely no grid electricity or fossil fuel inputs to operate. The WHO and UNICEF Joint Monitoring Programme (JMP) classifies these as foundational to achieving SDG 6 (WHO/UNICEF, 2021). Because they consume negligible amounts of water relative to industrial or agricultural uses and require zero energy, they are physically incapable of causing resource or technological lock-in.

2.2.3 | Smallholder Agriculture and Land Use

a. **Context:** Massive commercial afforestation or monoculture cash-crop expansion can cause Indirect Land Use Change (ILUC), strain local watersheds, and threaten regional food security.

b. **Literature:** Smallholder farming operates on a fundamentally different risk paradigm. The Food and Agriculture Organization (FAO) universally defines smallholder family farms as operating on non-contiguous plots of ≤ 5 hectares. Interventions targeting regenerative soil practices, agroforestry, or subsistence crop-rotation on these micro-plots inherently prevent the monopolization of arable land (FAO, 2014). Such decentralized projects enhance soil organic carbon and local food security rather than crowding it out.

2.2.4 | Distributed Off-Grid Power

a. **Context:** Extending national electrical grids to remote, deeply impoverished rural areas is often economically prohibitive in the short-to-medium term, leading to reliance on toxic kerosene lamps.

b. **Literature:** The Global Off-Grid Lighting Association (GOGLA) and the World Bank report that Pico-Solar and Nano-Solar Home Systems (SHS) (typically under 100 watts) and standalone solar lanterns are the most rapid, low-carbon mechanisms for achieving basic energy access (SDG 7) in off-grid regions (World Bank, 2022). Because they are entirely modular, off-grid, and do not draw from or burden national renewable energy capacities, they lack any mechanism to cause structural lock-in.

2.3 | Recommended "Lock-in Safe" Positive List Matrix

Based on the synthesis of institutional literature, it is recommended that the following matrix be formally adopted as Annex B to the GS4GG PAA MT400-XX Methodology Tool. Activities employing these exact technologies exclusively automatically qualify for Track A (Fast-Track Assessment).

Table 1: GS4GG "Lock-in Safe" Positive List (Recommended Annex B)

Sector	Eligible "Lock-in Safe" Technologies / Practices	Scientific & Lock-in Justification
Household Energy & Clean Cooking	• Advanced Biomass/Pellet Cookstoves (ISO Tier 3+) • Household Biogas Digesters (≤15m³ volumetric capacity) • Solar Cookers and Solar Water Heaters	Operates on localized waste or ambient energy; lacks centralized infrastructure; capital turnover is fast enough to allow future substitution without sunk-cost inertia.

WASH (Water & Sanitation)	• Point-of-use (POU) water purification systems (e.g., ceramic/gravity filters) • Manual, non-motorized boreholes and community handpumps	Requires zero operational energy input; water abstraction is statistically negligible compared to basin-level commercial/agricultural demands.
Agriculture & LUF	• Smallholder agroforestry, regenerative agriculture, and soil interventions implemented on non-contiguous plots of **≤5 hectares per participating farmer**.	Strict 5-hectare limit structurally prevents commercial monopolization of arable land, actively enhancing local food security rather than displacing it.
Distributed Power	• Pico/Nano-Solar Home Systems (SHS) and standalone off-grid Solar Lanterns.	100% off-grid; displaces baseline kerosene use while consuming zero megawatt-hours of the host country's public renewable energy grid capacity.

2.4 | Recommendations for Tool-Level Adoption

To ensure this Positive List functions smoothly in practice and resists exploitation, the Methodology Committee shall enforce the following integration rules within the tool text:

1. **Exclusivity Requirement:** Section 3.2.1 of the tool shall specify that an activity only qualifies for Track A via the Positive List if it *exclusively* employs the listed technologies. A project combining a smallholder agroforestry component with a massive 10,000-hectare commercial timber plantation cannot claim the Track A exemption for the entire project.
2. **Strict Boundary Enforcement:** The limits defined in Annex B (e.g., the ≤15m³ limit for biodigesters and the ≤5 hectare limit for smallholder plots) are absolute. If a developer groups a co-op of farmers into a single contiguous 500-hectare plantation, or builds a 50m³ commercial biodigester, the activity immediately loses its Annex B status and shall undergo Track B (Project-Level) assessment or be evaluated under Microscale limits (Annex C).
3. **Exclusion of Transitional Fossil Fuels:** The Positive List shall remain strictly zero-emission or sustainable-biomass based at the point of use. Technologies like Liquefied Petroleum Gas (LPG) cookstoves or high-efficiency diesel mini-grids, while offering short-term health benefits, still constitute a fossil-fuel pathway and therefore *cannot* be added to the Positive List. They shall be evaluated under Track B to ensure alignment with host country LT-LEDS phase-out dates.
4. **Review Mechanism:** As with all parameters in the Annex, this list shall be reviewed every three years. If a technology scales unexpectedly in a way that

begins to threaten resource pools, it shall be amended or removed during the schedule update cycle.

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3| PRE-VERIFIED PATH DEPENDENCY MACRO-INDICATORS (ANNEX D):

SUMMARY

Under Step 3 (Contextualized GHG Intensity Assessment) of the *Gold Standard for the Global Goals (GS4GG) Methodology Tool: Analysis of Lock-in Risk* (GS4GG PAA MT400-XX), mitigation activities with operational lifetimes exceeding 10 years shall demonstrate that they employ the technology or practice with the lowest greenhouse gas (GHG) intensity. To ensure an equitable assessment that does not penalize projects in developing nations, Phase B of this step incorporates a "Path Dependency Filter." This mechanism allows developers to exclude theoretical, globally advanced baseline alternatives if they are physically, structurally, or socio-economically impossible to implement locally. However, requiring individual developers to conduct bespoke feasibility studies to "prove a negative" (e.g., proving that an advanced supply chain does not exist) introduces prohibitive transaction costs and subjective validation disputes. This supplementary research report synthesizes institutional literature on technological diffusion barriers, infrastructural deficits, and biophysical constraints to establish a set of Pre-Verified Macro-Indicators. By leveraging standardized datasets from the United Nations (UN), World Bank, and World Resources Institute (WRI), this report formally defines the objective triggers that automatically exempt developers from considering inapplicable frontier technologies. It culminates in a recommended matrix for formal adoption as Annex D of the tool.

3.1 | Introduction and Procedural Context

Carbon lock-in is fundamentally driven by "path dependency"—the phenomenon where historical infrastructure, supply chains, and socio-economic contexts dictate future technological choices (Unruh, 2000). In the context of global carbon markets, assuming a uniform "Best Available Technology" (BAT) across all geographies is scientifically flawed. A technology that represents the baseline in Western Europe (e.g., grid-tied induction heating, large-scale electric boilers, or Direct Air Capture) may be structurally impossible to implement in Sub-Saharan Africa due to an absent electrical grid or missing specialized maintenance supply chains (Ockwell et al., 2018).

While the *GS4GG Analysis of Lock-in Risk Tool* rightly allows developers to filter out impossible alternatives, placing the entire burden of proof on the developer creates a severe "complexity barrier." Verification and Validation Bodies (VVBs) often demand extensive, highly localized market studies to verify that a technology is truly unavailable. To resolve this validation bottleneck, GS4GG provides a normative set of pre-verified macro-indicators. If a host region hits a recognized statistical trigger, certain classes of technology are automatically excluded from the alternative scenario analysis, bypassing the need for project-level proof and reducing the transaction costs of climate finance

3.2 | Methodology of the Literature Review

To identify macro-indicators that are scientifically defensible, objective, and auditable by VVBs, the literature review focused on institutional frameworks tracking global technological capacity and infrastructural development. The selection of indicators was governed by three strict criteria:

1. **Authoritative and Institutional Origins:** Indicators shall be maintained by globally recognized bodies (e.g., UN, World Bank, WRI) to ensure absolute neutrality and prevent developer manipulation.
2. **Public Accessibility:** The underlying datasets shall be publicly available and regularly updated so developers and VVBs can easily cross-reference them without paywalls.
3. **Proxy Validity & Conservativeness:** The indicator shall serve as a robust, peer-reviewed proxy for severe physical, structural, or biophysical constraints (explicitly excluding purely financial barriers, which are handled separately under GS4GG Financial Additionality tests).

3.3 | Review of Authoritative Path Dependency Indicators

3.3.1 | Technological and Supply Chain Constraints: The LDC/SIDS Classification

a. **Constraint:** The deployment of frontier mitigation technologies—such as Direct Air Capture with Carbon Storage (DACCS), Bioenergy with CCS (BECCS), and Green Hydrogen networks—requires massive, specialized supply chains, advanced domestic R&D bases, and highly skilled maintenance labour.

b. **Literature:** The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) explicitly notes that the deployment of advanced engineered removals and complex bio-refineries is heavily constrained in developing nations due to technology transfer barriers and an absence of local supply chains (IPCC, 2022). Furthermore, the United Nations Conference on Trade and Development (UNCTAD) *Technology and Innovation Report* demonstrates a severe "frontier technology readiness" gap, noting that Least Developed Countries (LDCs) and Small Island Developing States (SIDS) inherently lack the industrial base required to deploy, maintain, or absorb these technologies without complete reliance on unsustainable, imported turnkey solutions (UNCTAD, 2023).

c. **Indicator:** Host country classification on the active UN-OHRLLS List of LDCs or SIDS.

3.3.2 | Infrastructural Constraints: Rural Electrification Rates

a. **Constraint:** Many global climate pathways assume the mass electrification of end-use sectors (e.g., replacing fossil-fuel boilers with electric boilers, or transitioning from biomass cookstoves to electric induction). However, in regions suffering from severe energy poverty, these theoretical alternatives are structurally impossible.

b. **Literature:** According to the World Bank's Energy Sector Management Assistance Program (ESMAP) and the Tracking SDG7 reports, national grid extension in Sub-Saharan Africa and parts of South Asia often lacks the capacity, reliability, and sheer geographic reach to support intensive new loads (World Bank, 2024; IEA, 2023). Engineering models demonstrate that in sub-national regions where the baseline rural electrification rate is below 50%, the existing grid architecture is categorically incapable of absorbing continuous, high-draw industrial or commercial electric alternatives without catastrophic load-shedding and transformer failures (Pachauri et al., 2021; Blimpo & Cosgrove-Davies, 2019).

c. **Indicator:** Sub-national regional rural electrification rate of < 50%, as tracked by the World Bank Open Data (SDG Indicator 7.1.1).

3.3.3 | Biophysical and Geographic Limits: Baseline Water Stress

a. **Constraint:** Certain theoretical mitigation alternatives are heavily dependent on local natural capital, particularly freshwater. Liquid-solvent DACCS facilities consume up to 50 tonnes of water per tonne of CO_2 captured. Massive irrigated commercial afforestation (ARR) or dedicated bioenergy crops possess similarly massive evapotranspiration footprints (Smith et al., 2016).

b. **Literature:** The water-energy-emissions nexus is a highly documented limit to mitigation pathways. Stenzel et al. (2021) and Rosa et al. (2020) demonstrate that deploying high-water-footprint mitigation technologies in arid regions actively exacerbates local water stress and threatens agricultural viability, rendering them fundamentally maladaptive. The World Resources Institute (WRI) Aqueduct Water Risk Framework is the premier geospatial tool used globally for corporate and regulatory water risk assessments. Catchments classified by WRI as experiencing "High" (40–80%) or "Extremely High" (>80%) baseline water stress lack the surplus hydrological carrying capacity to support wet-cooled power plants, liquid-solvent DACCS, or large-scale irrigated monocultures (WRI, 2024).

c. **Indicator:** Catchment classification of "High" or "Extremely High" Baseline Water Stress on the WRI Aqueduct Atlas.

3.4 | Recommended Pre-Verified Path Dependency Matrix

Based on the synthesis of institutional methodologies and socio-economic realities, it is recommended that the following matrix be formally adopted as Annex D to the GS4GG PAA MT400-XX Methodology Tool. When evaluating alternative scenarios in Step 3 (Phase B), developers may claim these triggers to automatically filter out inapplicable technologies.

Table 1: Pre-Verified Path Dependency Macro-Indicators (Recommended Annex D)

Macro-Indicator (Data Source)	Trigger Condition	Resulting Automatic Exclusions from Alternative Scenario Modelling	Scientific & Institutional Basis
1. UN LDC/SIDS Classification *(Source: UN-OHRLLS)*	Host country is currently classified on the active list as a Least Developed Country (LDC) or Small Island Developing State (SIDS).	Excludes all pre-commercial, highly capital-intensive, or proprietary technologies requiring advanced domestic maintenance supply chains (e.g., DACCS, Green Hydrogen, advanced BECCS, large-scale CCS).	UNCTAD (2023); IPCC WGIII (2022) Chapter 16 identifying extreme tech transfer barriers.
2. Regional Electrification Rate *(Source: World Bank Open Data / SDG 7)*	Project is located in a sub-national region where the rural electrification rate is < 50%.	Excludes all continuous, grid-dependent alternatives (e.g., grid-tied electric industrial boilers, full-scale residential induction cooking networks).	World Bank ESMAP (2024); Pachauri et al. (2021) regarding grid fragility and baseload absence.
3. Baseline Water Stress Index *(Source: WRI Aqueduct Atlas)*	Project is located in a catchment area formally classified as "High" (40-80%) or "Extremely High" (>80%) baseline water stress.	Excludes all highly water-consumptive alternatives (e.g., liquid-solvent DACCS, wet-cooled thermal power generation, massive irrigated monoculture/ARR).	WRI (2024); Rosa et al. (2020); Stenzel et al. (2021) regarding absolute biophysical limits.

3.5 | Recommendations for Tool-Level Adoption

To ensure these indicators successfully reduce the burden of proof for developers without creating auditing loopholes, the Methodology Committee should integrate the following rules into the tool's governance framework:

a. **Mandatory VVB Acceptance:** The core text of the tool (Section 5.4 and Section 6.3) shall explicitly state that if a developer provides a verifiable link/screenshot to the WRI Aqueduct, World Bank, or UN database proving their project location meets a trigger condition, the VVB shall accept the exclusion of the corresponding technology.
b. **Sub-National Granularity:** For Indicator 2 (Electrification Rate) and Indicator 3 (Water Stress), developers shall be directed to use sub-national or catchment-level data where available, rather than national averages. A country may have a national electrification rate of 75% driven by its capital city, but the

specific rural province where the project is located may sit at 15%. The local reality dictates the path dependency.

c. **Explicit Exclusion:** While LDC classification acts as a proxy for supply-chain and structural capital vacuums, the tool text shall explicitly remind developers that in non-LDC/non-SIDS countries, *high financial cost alone* is not a valid path dependency filter. Financial additionality is tested under separate GS4GG standards; the lock-in tool tests physical, biophysical, and macro-structural impossibilities.
d. **Synchronization with the 3-Year Update Cycle:** Because a country's status may change (e.g., graduating from LDC status, or improving rural electrification), the validity of a project's path dependency claim shall be evaluated based on the datasets published at the exact time the project is submitted for initial validation or crediting period renewal.

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4| REGIONAL BEST AVAILABLE TECHNOLOGY (BAT) BENCHMARKS (ANNEX E):

SUMMARY

Under Step 3 (Contextualized GHG Intensity Assessment) of draft tool *Gold Standard for the Global Goals (GS4GG) Methodology Tool: Analysis of Lock-in Risk* (GS4GG PAA MT400-XX), Track B mitigation activities with operational lifetimes exceeding 10 years shall definitively prove they employ the technology or practice with the lowest feasible greenhouse gas (GHG) intensity. Typically, demonstrating this requires developers to execute complex, multi-scenario lifecycle emission models comparing their project against all commercially available alternatives. To eliminate this prohibitive validation burden, Step 3, Option 1 allows developers to bypass mathematical modelling if their proposed activity meets an officially recognized "Best Available Technology" (BAT) benchmark. This supplementary research report provides the scientific and regulatory justification for standardizing these absolute BAT thresholds. Through a systematic review of the EU Taxonomy for Sustainable Activities, European BREF (Best Available Techniques Reference) documents, the International Energy Agency (IEA), and the Intergovernmental Panel on Climate Change (IPCC), this report defines ultra-conservative, sector-specific GHG intensity limits. It culminates in a formally recommended BAT Matrix to be adopted as Annex E of the tool.

4.1 | Introduction and Procedural Context

The fundamental objective of the *GS4GG Lock-in Risk Tool* is to prevent carbon finance from subsidizing long-lived infrastructure that is only marginally better than the baseline. Carbon markets have historically struggled with the "technological lock-in" of transitional fuels—for example, funding a highly efficient natural gas plant that operates for 30 years, ultimately displacing the adoption of zero-emission renewables and consuming a vast portion of a host country's remaining carbon budget (Erickson et al., 2015).

To enforce strict environmental integrity, Step 3 requires projects to adopt the absolute lowest GHG intensity technology feasible in their region. However, forcing individual developers to calculate the precise lifecycle emissions of five to ten counterfactual technologies to prove their choice is the "best" introduces massive transaction costs and subjective disputes during Verification and Validation Body (VVB) audits.

By establishing normative **Regional BAT Benchmarks (Annex E)**, GS4GG shifts from subjective modelling to an objective, pass/fail threshold. If a developer deploys a technology that meets or outperforms the globally or regionally established BAT benchmark, it is statistically impossible for the project to represent a lock-in risk, and it automatically passes Step 3.

4.2 | Methodology of the Literature Review

Defining "Best Available Technology" is highly contested, as it blends theoretical engineering limits with commercial and economic feasibility. To ensure GS4GG benchmarks remain unassailable, the literature review relied exclusively on institutional regulatory frameworks rather than individual, theoretical academic models. The selection criteria included:

a. **Regulatory Primacy:** Benchmarks derived from enforceable compliance market standards—specifically the European Union’s Industrial Emissions Directive (IED) and the EU Taxonomy for Sustainable Finance—were prioritized, as they have already survived rigorous multi-stakeholder peer review and legal scrutiny.

b. **Technological Neutrality & Absolute Output Metrics:** Rather than prescribing specific brand-name technologies (which violates GS4GG neutrality rules), the review isolated *absolute output metrics* (e.g., gCO_2e/kWh or % thermal efficiency) that define the performance of the highest-tier technologies.

c. **Regional Contextualization:** Where appropriate, benchmarks were adjusted for Non-Annex I (developing) countries. A technology that is BAT in a highly developed economy (e.g., advanced robotic sorting and plasma gasification for municipal waste) is not a practical benchmark for a Least Developed Country (LDC) currently relying on unmanaged open dumps.

4.3 | Review of Authoritative BAT Benchmarks by Sector

4.3.1 | Grid Power Generation

a. **The Regulatory Benchmark:** The EU Taxonomy for Sustainable Activities establishes the global gold standard for evaluating whether power generation contributes substantially to climate change mitigation. Under the Taxonomy, a generation facility is only deemed sustainable and aligned with a net-zero trajectory if its lifecycle emissions fall below the absolute threshold of 100g CO_2e per kWh (European Commission, 2021).

b. **Scientific Consensus:** The IEA's Net Zero by 2050 Roadmap confirms that global electricity grids shall reach an average intensity well below 100g CO_2e/kWh by 2030 to remain aligned with the 1.5°C Paris target (IEA, 2023). Technologies meeting this ultra-strict BAT benchmark exclusively include wind, solar PV, geothermal, and strict run-of-river hydropower. Unabated fossil fuels (including "efficient" combined-cycle natural gas, which averages 350–400g CO_2e/kWh) categorically fail this threshold.

4.3.2 | Solid Waste Management (Contextualized for Non-Annex I Nations)

a. **The Regulatory Benchmark:** In developed nations, BAT for municipal solid waste (MSW) involves total diversion, source-segregation, and anaerobic digestion. However, in Non-Annex I nations, the baseline is typically open dumping or unmanaged landfills with zero gas capture, leading to massive fugitive methane emissions.

b. **Scientific Consensus:** The Global Methane Initiative (GMI) and US EPA Landfill Methane Outreach Program (LMOP) dictate that a well-designed, actively vacuum-pumped Landfill Gas (LFG) extraction system can achieve a lifetime collection efficiency of 75-85% (US EPA, 2024; IPCC, 2019). Setting the BAT at > 70% active capture with enclosed flaring or energy utilization represents the highest tier of practically achievable engineering for engineered sanitary landfills operating with mixed-waste streams in developing regions. Alternatively, completely avoiding methane generation via controlled aerobic composting inherently qualifies as BAT for the organic fraction (CCAC, 2021).

4.3.3 | Industrial Heat and Steam Generation

a. **The Regulatory Benchmark:** Industrial heat is notoriously difficult to decarbonize. The European Integrated Pollution Prevention and Control (IPPC) Bureau publishes BAT Reference Documents (BREFs) under the Industrial Emissions Directive. The BREF for Large Combustion Plants dictates that the absolute highest tier of thermal efficiency for industrial boilers ranges between 85% and 92% (European IPPC Bureau, 2017).

b. **Scientific Consensus:** High thermal efficiency alone is insufficient to prevent carbon lock-in if the fuel source is fossil-based (e.g., an 85% efficient coal boiler). To align with the IEA's industrial decarbonization pathways, BAT shall combine top-tier mechanical efficiency with a zero-emission fuel switch. Therefore, the BAT benchmark requires the combination of **> 85% thermal efficiency** utilizing **100% sustainable waste biomass residues** or **100% renewable electricity** (e.g., electric arc furnaces or industrial heat pumps) (IEA, 2022).

4.4 | Recommended Regional BAT Benchmarks Matrix

Based on the synthesis of institutional literature and regulatory standards, it is recommended that the following matrix be formally adopted as **Annex E** to the *GS4GG PAA MT400-XX* Methodology Tool.

Table 1: Regional Best Available Technology (BAT) Benchmarks (Recommended Annex E)

Sector	Global / Regional Context	Default BAT Benchmark Step 3 (Option 1)	Authoritative Justification
Grid Power Generation	Global (All Regions)	Lifecycle emission intensity of **< 100g CO_2e/kWh** (e.g., Wind, Solar, strict Hydro).	Aligns with the EU Taxonomy threshold for substantial contribution to climate mitigation (European Commission, 2021; IEA, 2023).
Waste Management	Non-Annex I Countries	**> 70% active capture and flaring/utilization** of	Represents the highest achievable engineered collection

	(Developing Economies)	Landfill Gas (LFG) over the crediting period, OR controlled aerobic composting.	efficiency under US EPA LMOP and IPCC guidelines (IPCC, 2019; US EPA, 2024).
Industrial Heat & Steam	Global (All Regions)	Emission intensity equivalent to a high-efficiency plant (**> 85% thermal efficiency**) utilizing **100% sustainable waste residues or renewable electricity**.	European IPPC Bureau Large Combustion Plant BREF (2017); IEA Industrial Decarbonization Pathways (2022).

4.5 | Recommendations for Tool-Level Adoption

To ensure environmental integrity and optimal usability during VVB audits, the requirements should enforce the following operational directives regarding Annex E:

1. **Exemption from Multi-Scenario Modelling:** Section 6.3.2 (Step 3, Option 1) of the tool shall explicitly instruct VVBs that if a project developer submits engineering specifications or life-cycle assessments proving their technology meets or outperforms the relevant BAT metric in Annex E, the project immediately passes Step 3. The VVB **shall not** require the developer to calculate the emissions of alternative scenarios (Phase A, B, and C).
2. **Strict Enforcement of the Lifecycle Boundary:** For the Grid Power Generation benchmark (< 100g CO_2e/kWh), the tool shall specify that this metric applies to *lifecycle emissions* (including upstream fugitive emissions, manufacturing supply chains, and methane leakage), not just point-of-combustion stack emissions. This intentionally ensures that "efficient" natural gas plants cannot artificially manipulate baseline boundaries to meet the BAT threshold.
3. **The 3-Year Ratchet Mechanism:** Because BAT is a moving target driven by global R&D and declining clean-tech costs, these thresholds shall be subject to the strict 3-year update cycle established in the Digital Parameter Annex governance rules. At the 2029 review, if grid storage technologies mature significantly, the power generation BAT threshold may be ratcheted downward from 100g to 50g CO_2e/kWh.
4. **Non-Exhaustive Scope:** The tool shall clarify that Annex E is a *facilitative* list covering the most common high-volume GS4GG sectors, rather than an exhaustive universal list. If a developer's specific sector (e.g., maritime transport, cement manufacturing) is not listed in Annex E, they cannot use Option 1 and shall proceed to Option 2 (Project-Level Context-Filtered Assessment) to prove they are utilizing the lowest GHG intensity technology feasible in their region.

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5| DEFAULT SAFE-SCALE THRESHOLDS FOR CRITICAL RESOURCES (ANNEX F)

SUMMARY

Under the newly drafted *Gold Standard for the Global Goals (GS4GG) Methodology Tool: Analysis of Lock-in Risk* (GS4GG PAA MT400-XX), mitigation activities undergoing a Project-Level Assessment (Track B) shall demonstrate that their scale and resource consumption do not "crowd out" a host country's broader sustainable development or long-term low-emission transition (Step 4). Section 6.4.2 (Option 1) allows activities to bypass complex, project-level macroeconomic modelling if their resource consumption falls below a predefined "safe harbour" scale threshold. This supplementary report presents default safe-scale thresholds for critical resources. Through a systematic literature review of environmental impact assessment (EIA) heuristics, resource carrying-capacity models, and normative frameworks from the Food and Agriculture Organization (FAO), World Resources Institute (WRI), International Renewable Energy Agency (IRENA), and the International Energy Agency (IEA), this report defines scientifically backed, conservative *de minimis* thresholds for arable land, freshwater, sustainable biomass, and renewable energy grid capacity. It concludes with a formalized Default Safe-Scale Threshold Matrix recommended for direct adoption into the tool.

5.1 | Introduction and Procedural Context

As carbon markets increasingly incentivize highly scalable Land Use and Forestry (LUF) activities and capital-intensive engineered carbon removals (e.g., Direct Air Capture [DACCS], Bioenergy with Carbon Capture and Storage [BECCS]), a novel dimension of lock-in risk emerges: Resource Lock-in. Even if a technology exhibits a low greenhouse gas (GHG) intensity, its massive scale can monopolize finite natural or structural resources. This monopolization can actively obstruct the host country's ability to meet local food security goals, provide equitable energy access, or fulfil the sectoral targets of its Nationally Determined Contribution (NDC) and Long-Term Low-Emission Development Strategy (LT-LEDS) (Dooley et al., 2022).

Step 4 of the GS4GG Analysis of Lock-in Risk Tool evaluates this risk. To reduce the validation burden on project developers for activities that are objectively too small to cause systemic resource crowding, the tool introduces a "Default Safe Harbor / Threshold Exemption" (Option 1). This report operationalizes that exemption by establishing quantitative threshold benchmarks below which an activity's resource consumption is deemed macro-economically insignificant.

5.2 | Methodology of the Literature Review

The establishment of default thresholds relies on the concept of "carrying capacity" and *de minimis* impact, which is heavily utilized in cumulative environmental impact assessments (CEIA). The review was governed by the following parameters:

1. **Conservativeness:** Given that carbon finance operates globally—often in regions with weak institutional data or governance—thresholds were calibrated

to the strict lower bounds of acceptable extraction rates to prevent cumulative local depletion.

2. **Relative vs. Absolute Metrics:** While absolute limits (e.g., specific hectare caps or megawatt limits) are simpler for Verification and Validation Bodies (VVBs) to audit, relative limits (e.g., percentage of a regional basin's capacity) are more scientifically robust and context-aware. This report recommends a dual-metric approach, providing both relative percentages and absolute operational caps.
3. **Targeted Resources:** The review strictly bounds its analysis to the four "Critical Resources" explicitly defined in Section 6.4.1 of the GS4GG Tool: Arable Land, Freshwater, Sustainable Biomass, and Renewable Energy Grid Capacity.

5.3 | Review of Authoritative Thresholds by Critical Resource

5.3.1 | Arable Land and Food Security

Large-scale land acquisition for afforestation/reforestation (ARR) or commercial bioenergy poses severe risks to local food security and indigenous land tenure, often precipitating indirect land-use change (ILUC) (IPCC, 2019). The FAO’s Voluntary Guidelines on the Responsible Governance of Tenure emphasize that "large-scale" land acquisitions typically exceed 1,000 hectares (ha) in densely populated developing regions, at which point socio-economic disruptions become statistically probable (FAO, 2012). Furthermore, spatial ecosystem modelers generally concur that converting more than 5% of a sub-national district’s available surplus non-forested land to a single commercial sink heavily risks displacing local agriculture into pristine frontiers (Searchinger et al., 2015). For a safe harbour exemption, an activity shall remain well below these macro-scale triggers.

5.3.2 | Local Freshwater Availability

Mitigation technologies, particularly water-cooled industrial processes and engineered removals, possess massive water footprints. For instance, DACCS facilities using liquid solvent systems require up to 50 tonnes of water per tonne of CO2 captured, while immense ARR plantations can permanently alter local watershed hydrology (Smith et al., 2016; Stenzel et al., 2021). The World Resources Institute (WRI) Aqueduct Water Risk Framework classifies baseline water stress by dividing total water withdrawals by available renewable surface and groundwater. According to established water-footprint accounting principles, a single commercial or industrial project abstracting less than 1% of the locally available renewable water resource (or < 5% of the total unallocated surplus in the catchment) is generally considered to have a negligible, de minimis impact on basin-level water stress (Hoekstra et al., 2011; WRI, 2019).

5.3.3 | Sustainable Biomass Supply

Biomass energy, biochar, and BECCS rely heavily on agricultural or forestry residues. However, extracting excessive residues depletes soil organic carbon (SOC) and increases local fertilizer dependencies. IRENA and IEA Bioenergy task forces recommend that no more than 30% to 40% of agricultural residues be removed from a field to maintain soil health (IRENA, 2022). At a regional scale, a single facility should not monopolize the market for local residues. Industrial ecology frameworks suggest that consuming less than 5% of the safely extractable regional surplus of waste biomass prevents supply-chain monopolization and safeguards feedstock prices for local, non-climate economic uses (Bentsen et al., 2014).

5.3.4 | Renewable Energy Grid Capacity

Engineered removals are deeply energy-intensive; DACCS requires approximately 2,000 kWh per tonne of CO_2 captured (Realmonte et al., 2019). Connecting such facilities to a capacity-constrained national grid risks "cannibalizing" the clean energy needed to decarbonize local households and baseline industries. The IEA's Net Zero by 2050 framework indicates that large industrial users shall deploy dedicated, behind-the-meter generation. However, for grid-connected mitigation activities, drawing less than 1% of the host regional grid's installed renewable energy capacity serves as a conservative benchmark to ensure the activity does not measurably derail the host country's public grid decarbonization pathways (IEA, 2023).

5.4 | Recommended Default Safe-Scale Threshold Matrix

Synthesizing the literature, the following absolute and relative thresholds are recommended for adoption. To qualify for the Fast-Track Option 1 exemption under Step 4 of the tool, an activity shall demonstrate its consumption falls below the threshold for its relevant sector.

Table 1: GS4GG Default Safe-Scale Thresholds for Critical Resources

Critical Resource	Relevant Mitigation Sectors	Relative Threshold (Contextual)	Absolute Safe Harbor Cap (Default)	Authoritative Justification
Arable Land	Commercial LUF, ARR, Bioenergy Crops	< 5% of the district/municipality's available, unallocated non-forested arable land.	< 500 hectares of contiguous land acquisition.	Prevents displacement of food production and ILUC (Searchinger et al., 2015; FAO, 2012).
Freshwater	Engineered Removals (DACCS), Large-Scale Irrigation / ARR	< 1% of the available renewable freshwater yield of the local catchment/aquifer.	< 100,000 m^3 / year total net consumptive withdrawal.	Ensures no exacerbation of local basin water stress (Hoekstra et al., 2011; WRI, 2019).
Sustainable Biomass	Biochar, Biomass Power, BECCS	< 5% of the safely extractable, surplus waste biomass in the project's sourcing radius.	< 10,000 tonnes / year of dry biomass consumption.	Protects soil organic carbon retention and local feedstock markets (IRENA,

				2022; Bentsen et al., 2014).
Renewable Energy Grid Capacity	Green Hydrogen, DACCS, High-Heat Electrification	< 1% of the host region's installed grid-connected renewable energy capacity.	< 5 MW of continuous grid-connected power demand.	Prevents cannibalization of the public green energy transition (IEA, 2023; Realmonte et al., 2019).

5.5 | Recommendations for Tool-Level Adoption

To effectively operationalize these thresholds within the *GS4GG PAA MT400-XX* methodology tool and ensure strict compliance during the validation process, the following normative integration rules are recommended for the Methodology Committee:

a. Formalize the "OR" Applicability: Section 6.4.2 (Option 1) should be updated to state that a project passes Step 4 if it meets the qualitative conditions (e.g., exclusively relies on waste biomass, exclusively implemented on officially degraded land) OR if its resource use falls strictly below *either* the Relative Threshold *or* the Absolute Safe Harbor Cap listed in Table 1.
b. Burden of Proof on Activity Developer: The tool shall state that developers electing to claim the "Relative Threshold" (e.g., < 1% of catchment water) shall utilize officially recognized spatial mapping tools (e.g., WRI Aqueduct Water Risk Atlas) or recent governmental baseline statistical data. If reliable regional baseline data is unavailable or outdated in the host country, the developer *shall* default to the stricter Absolute Safe Harbor Cap.
c. Cumulative Scale Aggregation (Anti-Fractionalization Clause): To prevent project disaggregation (i.e., splitting a massive 5,000-hectare plantation into ten 500-hectare projects to abuse the Option 1 exemption), the tool shall contain a cumulative safeguard. The thresholds shall apply to the *cumulative* resource draw of all carbon projects operated by the same developer (or its subsidiaries/affiliates) within the same geographic district or hydrological catchment area over a rolling 5-year period.
d. Exceeding Thresholds is Not Automatic Disqualification: It shall be clearly stated in the methodology text that failing to meet these Safe Harbor thresholds does not render a project ineligible. It simply indicates the project operates at a macroeconomic scale that necessitates the rigorous, fully documented socio-economic and resource modelling mandated in Step 4, Option 2 (Project-Level Assessment).

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